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SELF-LUBRICATING COATINGS PREPARED BY PLASMA  
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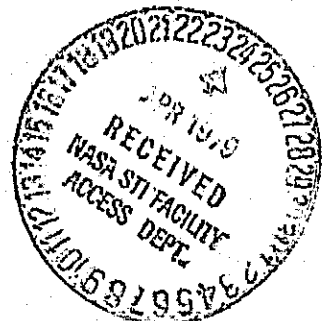
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**WIDE-TEMPERATURE-SPECTRUM SELF-  
LUBRICATING COATINGS PREPARED  
BY PLASMA SPRAYING**

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# WIDE-TEMPERATURE-SPECTRUM SELF-LUBRICATING

## COATINGS PREPARED BY PLASMA SPRAYING

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### ABSTRACT

Self-lubricating, multicomponent coatings, which lubricate over a wide range of operating conditions, are described. The coatings have been successfully applied by plasma-spraying mixed powders onto superalloy substrates. They have been evaluated in friction and wear experiments, and in sliding contact bearing tests. These coatings are wear resistant by virtue of their self-lubricating characteristics rather than because of extreme hardness; a further benefit is low friction. Experiments with simple pin on disk sliding specimens and oscillating plain cylindrical bearing tests were performed to evaluate the tribological properties of the coatings. It was shown that coatings of nichrome, glass and calcium fluoride are self-lubricating from about 500° to 900° C, but give high friction at the lower temperatures. The addition of silver to the coating composition improved the low temperature bearing properties and resulted in coatings which are self-lubricating from cryogenic temperatures to at least 870° C; they are therefore "wide temperature spectrum," self-lubricating compositions.

### INTRODUCTION

There is a current trend to design higher temperature engines because of their potential for significantly improved energy efficiency (Refs. 1 and 2). A critical and difficult problem with increasing engine temperatures is the need to develop improved high temperature materials including lubricants and bearing materials.

Most lubricating oils degrade oxidatively above 250° C. For higher temperatures, solid lubricant coatings and self-lubricating composites are needed. A complicating factor is that lubrication must not only be effective at the normally high operating temperatures but also at low temperatures during engine starting and warmup. In another kind of application, airframe bearings for the space shuttle, the lubricant must be functional in the vacuum of space as well as in air over a wide temperature spectrum.

Past research on high temperature solid lubricants at this laboratory demonstrated that fused calcium fluoride-barium fluoride coatings of 0.001 to 0.002 cm thickness are effective as lubricants from about 500° to 930° C (e.g., Ref. 3). The incorporation of finely dispersed silver particles into the coating microstructure improved low temperature friction and wear (Ref. 4). Composites of porous sintered

nickel base alloys infiltrated with the same fluorides were also self-lubricating above 500° C and sometimes had an advantage over thin coatings because fresh lubricant is replenished at the rubbing surface by the wear process itself (Ref. 5). However, composites can be difficult to prepare, and the composite body is structurally weaker and less dimensionally stable than a coated, dense metal part.

In this paper, plasma sprayed, multicomponent coating systems, which combine the in-depth lubricating ability of composites with the strength of a dense metal substrate, are described. The coatings are typically 0.025 cm thick; their composite nature provides freedom in optimizing the formulations for use at high temperatures only or for use over a wide temperature spectrum.

## COATING PROCEDURE

Coatings were plasma-sprayed onto the flat surface of disks used in pin on disk friction and wear experiments and onto the cylindrical bore of plain spherical bearings. The pin on disk configuration and the bearing design are shown in schematically in Fig. 1. The surfaces to be coated were first sand blasted then plasma sprayed with a nichrome bond coat about 0.007 cm thick. An excess thickness of lubricant coating was then plasma sprayed on to the bond coat and finish ground back to a total coating thickness (bond coat plus lubricant) of 0.025 cm.

Two lubricant coating compositions will be discussed: (1) a high temperature coating, PS100 and; (2) a wide-temperature-spectrum coating, PS101. Their nominal compositions by weight are:

PS100: 67 nichrome, 16-1/2 calcium fluoride, 16-1/2 glass  
 PS101: 30 nichrome, 30 silver, 25 calcium fluoride, 15 glass  
 Glass: 58 SiO<sub>2</sub>, 21 BaO, 8 CaO, 13 K<sub>2</sub>O

The glass is a special formulation to provide high temperature oxidation protection to nichrome. Details for preparation of the glass are given in Ref. 6. Applicability of PS101 to lubrication of airframe bearings for the Space Shuttle is discussed in Ref. 7.

Plasma spray parameters for both coatings was done with argon as the arc gas and the powder carrier gas at flow rates of 1.3 m<sup>3</sup>/hr and 0.4 m<sup>3</sup>/hr, respectively. Arc current was 350 amperes at 24 volts. Target distance was 5 to 8 cm.

## RESULTS AND DISCUSSION

Bearing friction and wear was determined in moderate vacuum, in cold nitrogen gas, and in air. Facilities were not available for testing bearings in hard vacuum, but friction and wear experiments with a pin on disk apparatus were performed in vacuum down to  $4 \times 10^{-10}$  torr.

## Bearing Tests

Plasma sprayed coatings were sprayed on to the cylindrical bores of plain spherical bearings. The spherical element was allowed to float for self-alignment of the bearing during mounting in the test rig, but all relative sliding during the tests was between the journal and the coating. The bearing bore is 1.537 cm diameter and 1.9 cm long, a radial load of  $3.5 \times 10^7$  N/m<sup>2</sup> (5000 psi) was employed. Journal oscillation was  $\pm 15^\circ$  at a frequency of 1 hertz.

Effect of silver. - Figure 2 gives friction coefficients in air for a preoxidized but otherwise unlubricated bearing, and for bearings lubricated with PS100 and with PS101.

The oxide film on the preoxidized bearing provided some protection against galling for a time but the bearing seized at  $870^\circ$  C. Friction coefficients for the bearing lubricated with PS100 were lower at all temperatures and effective lubrication was achieved from about  $500^\circ$  to  $900^\circ$  C. The beneficial effect of silver in reducing low temperature friction while only moderately reducing maximum temperature capability of the coating system is illustrated by the data for PS101. Friction coefficients on the order of 0.2 were obtained at all temperatures from room temperature to  $870^\circ$  C.

Wide spectrum performance of PS101. - The friction and wear data for bearings with PS101 lubrication, which were tested in moderate vacuum, cold nitrogen gas and in air, are summarized in Table I.

The lowest bearing friction was observed in the  $5 \times 10^{-2}$  torr vacuum where the friction coefficient was 0.15. Wear rates tended to decrease with test duration. Total diametral bearing wear was  $4.5 \times 10^{-3}$  cm after 5000 oscillating cycles.

In cold nitrogen ( $-107^\circ$  C), friction coefficients were typically 0.22 and diametral wear after 5000 journal oscillations was  $3.8 \times 10^{-3}$  cm.

As previously discussed, friction coefficients in air from room temperature to  $870^\circ$  C were approximately 0.2 over the entire temperature range. Wear rates also were uniformly low over the entire temperature spectrum.

These results clearly demonstrate the versatility of PS101 for lubricating plain journal bearings over an exceptionally wide range of temperatures and atmospheric pressures.

## Pin on Disk Experiments

Vacuum atmosphere. - Figure 3(a) gives the frictional characteristics an Inconel 750 pin sliding on PS101 in a vacuum of  $4 \times 10^{-10}$  torr at room temperature. The following experimental conditions, which are known to promote adhesion in vacuum, were employed. The specimens were baked out in vacuum at  $1700^\circ$  C, allowed to cool to room temperature, then sputter-cleaned. The clean surfaces were then placed into contact under a 200 gm normal load for 72 hours before initiating sliding at a very low velocity of 0.13 cm/sec.

The friction trace shows no evidence of an initial, high friction spike, which would be indicative of a cold weld. The static friction coefficient was 0.21 and in repeated starts and stops, it was always within the observed scatter of dynamic friction coefficients. Friction coefficients were typically in the range of 0.13 to 0.25 with periodic spikes to 0.33. Essentially the same results were also observed at a higher sliding velocity of 1.6 cm/sec (Fig. 3(b)).

Friction was also measured at a specimen temperature of 170° C (Fig. 3(c)). Specimens were first baked out at 170° C for 18 hours in vacuum, then the friction experiments were conducted at the bake-out temperature and an ambient pressure of  $2 \times 10^{-7}$  torr. Again, there was no indication of adhesive welding between the Inconel 750 pin and the PS101 coating. Friction coefficients tended to be a little higher than at room temperature and were in the range of 0.16 to 0.38 with periodic spikes to 0.43.

Figure 3(d) gives the friction characteristics of preoxidized PS101 at room temperature and an ambient pressure of  $2 \times 10^{-8}$  torr. The disk was preoxidized by heat treating in air for 125 hours at 750° C. The specimens were then held in vacuum for 3 days prior to the friction experiments. Again, static friction coefficients were in the same range as dynamic friction coefficients which were 0.09 to 0.29 with periodic spikes to 0.38.

The variations in friction coefficient shown in Figs. 3(b) to (d) were periodic with a frequency equal to the disk rpm. However, the maximums tended to gradually diminish with sliding duration resulting in a lower average friction coefficient. We can conclude that each microscopic area on the coating wear surface had a characteristic friction coefficient which was readily resolved on the friction recordings because of low sliding velocities and the small contact areas in the pin on disk experiments. The complex microstructure of PS101 is shown in Fig. 4. Smearing of the softer phases (calcium fluoride and silver) was probably responsible for the gradual reduction in the average friction coefficient with increasing sliding duration.

The results of these vacuum experiments indicate there is little danger that PS101 surfaces will cold weld in vacuum applications. However, the local variations of friction caused by microstructural inhomogeneities are undesirable, especially under conditions of low velocity sliding and small area contact geometries. These variations in friction were not apparent in the bearing tests, probably because of the relatively large conformal contact area which averaged out effects of localized microstructural variations on the friction coefficient.

#### CONCLUDING REMARKS

1. Plasma-sprayed composite coatings have been developed, which are self-lubricating from cryogenic temperatures to 870° C. They can be used in air or vacuum.

2. Because the coatings are multicomponent, the compositions can be modified for optimum performance in a given application.


3. Slow sliding velocity experiments in hard vacuum in the  $10^{-8}$  to  $10^{-10}$  torr pressure range showed that friction coefficients varied locally with the microstructure of the coatings. This illustrates the need for future development of composite, plasma-sprayed coatings with a fine-grained, more uniformly dispersed microstructure.

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TABLE I. - PERFORMANCE SUMMARY FOR OSCILLATING PLAIN  
SLIDING BEARINGS SELF-LUBRICATED WITH A PLASMA-  
SPRAYED COATING IN VARIOUS ATMOSPHERES

[PS101 Coating: 30 Ag, 30 NiCr, 25 CaF<sub>2</sub>, 15 glass; 0.025 cm  
(0.010 in.) thick;  $3.5 \times 10^7$  N/m<sup>2</sup> (5000 psi) unit load,  $\pm 15^\circ$   
oscillation at 1 hertz.]

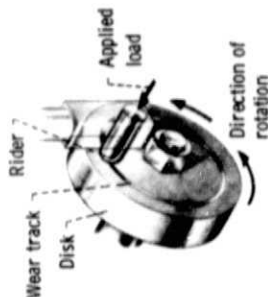
Bearing temperature		Ambient atmosphere	Typical friction coefficient	Increase in radial clearance	
				cm $\times 10^3$ (millinches)	
$^{\circ}\text{C}$	$^{\circ}\text{F}$			After 100 cycles	After 5000 cycles
Room	Room	Vacuum $5 \times 10^{-2}$ torr	0.15	1.3 (0.5)	4.5 (1.8)
-107	-160	Nitrogen	.22	0.3 (0.1)	3.8 (1.5)
Room	Room	Air	.24	.5 (0.2)	7.0 (2.8)
		760 torr			
540	1000		.19	.5 (0.2)	6.0 (2.4)
650	1200		.21	.3 (0.1)	2.5 (1.0)
870	1600		.23	.3 (0.1)	2.5 (1.0)





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(a) Oscillating journal bearing.



(b) Pin on disk.

Figure 1. - Coating friction and wear test configurations.

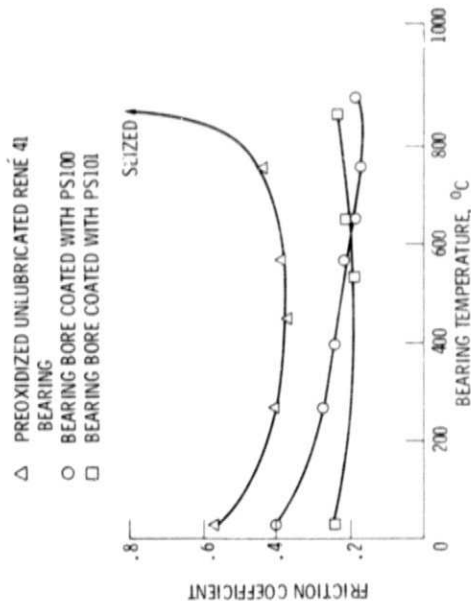


Figure 2. - Friction of bearings with and without plasma sprayed liners.

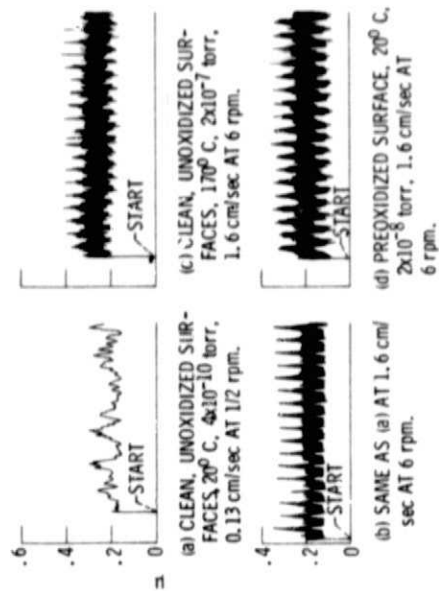
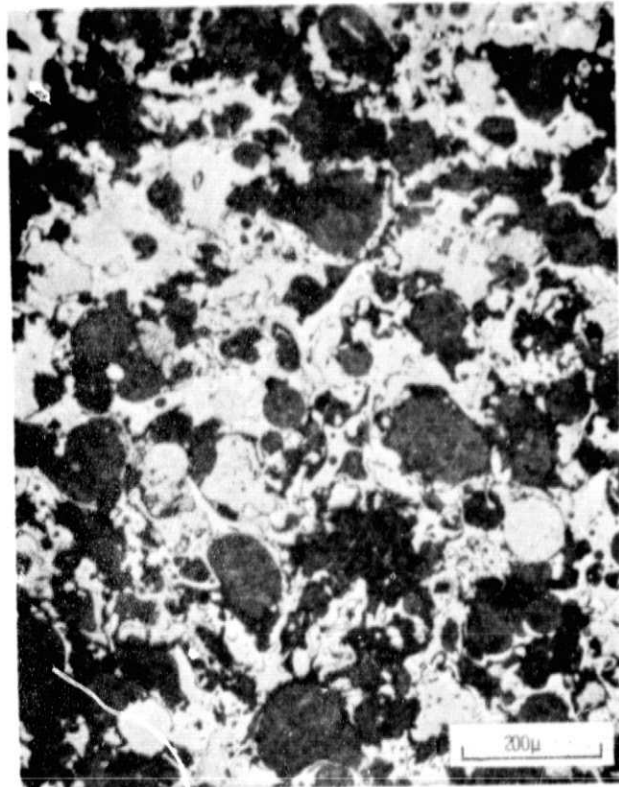
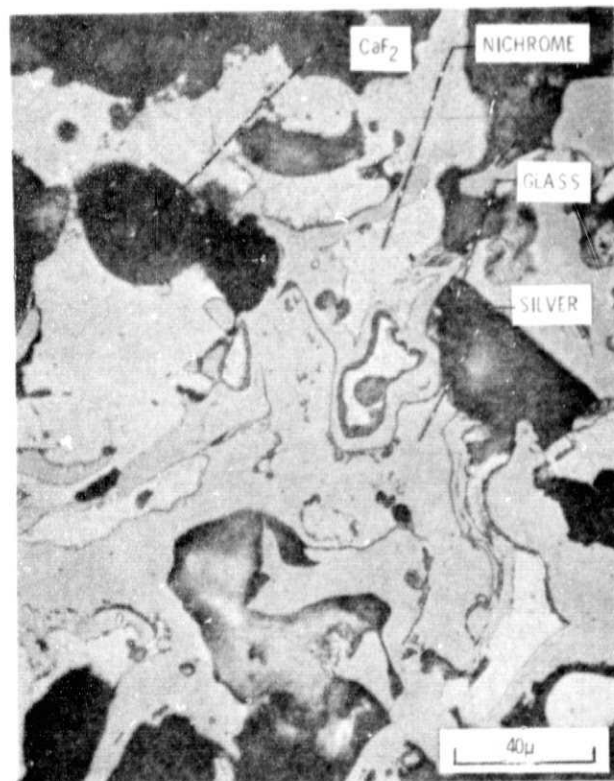


Figure 3. - Friction traces for Inconel 750 sliding on PS101 coatings in vacuum pin on disk experiments.

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(a) ORIGINAL MAGNIFICATION, 100X.



(b) ORIGINAL MAGNIFICATION, 500X.

Figure 4. - Microstructure of PS101.